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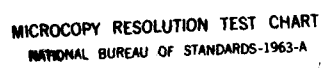
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Near Millimeter Wave Laser Action in n-GaAs

Final Report

Author: Fielding Brown
Professor of Physics
Williams College

Date: February 2, 1984

U.S. Army Research Office
Contract No. DAAG29 80 K 0082

Williams College
Williamstown, MA 01267

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Near Millimeter Wave Laser Action in n-GaAs

Gallium Arsenides

I. Statement of Problem

Work under this contract was initiated in an attempt to produce population inversion in epitaxial n-GaAs and to observe stimulated emission between the first excited state of donors and the ground state. The emitted ~~radiate~~^{an} would occur in the far infrared range of the spectrum where few laser sources are available. Such a source would be tuneable by magnetic tuning and would find application in spectroscopy and in communications.

radiation

II. Summary of Activity and Results

1. Far infrared photoconductivity in n-GaAs.

The photoconductivity of epitaxial n-GaAs ($n = 2.6 \times 10^{11} \text{ cm}^{-3}$) has been measured in response to high intensity ($P \sim 2.4 \text{ kW/cm}^2$) radiation at $\lambda = 95 \text{ } \mu\text{m}$. The saturation curve of photoconductivity versus excitation power yields a recombination time of 10^{-8} s, which is much shorter than the value predicted, 10^{-6} s, by the theory of the electron-phonon interaction. Recombination appears to occur from localized states as well as by capture of free conduction band electrons.

2. Attempts to observe FIR emission from optically pumped n-GaAs.

A careful study of the possibility of observing FIR emission from optically pumped n-GaAs was made using a high-power ($\sim \text{kW/cm}^2$) laser at $\lambda = 95 \text{ } \mu\text{m}$ as pumping source. So far no such radiation has been seen. We attribute the lack of success to two difficulties not foreseen at the outset of the research. The first involves the detection system used to look for stimulated emission. Under our pumping conditions, pump radiation consists of very short ($\sim 1 \text{ nsec}$) pulses occurring over a period of about 100 nsec. To properly resolve and observe these pulses it is necessary to have a detector of comparable speed. Unfortunately, the Putley detector used in these experiments only responded to pulses $\sim 20 \text{ nsec}$ or longer and was therefore not sufficiently sensitive for this work.

A second difficulty arose with regard to sample geometry. Epitaxial n-GaAs was obtained and prepared on substrates about $1/2 \text{ mm}$ thick with epi-layers of $65 \text{ } \mu\text{m}$. These were cut and stacked up to ten layers in an attempt to increase the active volume of material. This effort proved clumsy, and it was difficult to prepare smooth parallel surfaces on such stacks in order to provide laser mirrors to enhance the anticipated stimulated emission. This difficulty with material geometry has been chiefly responsible for our subsequent turn toward seeking stimulated emission in n-Ge as opposed to n-GaAs. In n-Ge there are no such material problems.

3. Study of possibility for stimulated emission in n-Ge.

A series of calculations has been undertaken to determine whether laser action in the far infrared could be observed from n-type germanium. These calculations have formed the basis of a new proposal which has subsequently been funded by National Science Foundation.

Calculations include: (1) a study of the optical pumping process, (2) the heating of conduction electrons, (3) excited state populations and population inversions, (4) gain coefficients on selected transitions, (5) projected laser losses, and (6) the several possibilities for tuning, e.g. magnetic tuning or stress tuning.

These calculations are mentioned under IV below and include an abstract, a table of contents, an "introduction," and a bibliography, all of which have been submitted to National Science Foundation as part of a research proposal. The proposal has since been funded.

III. Publication:

"Saturation of far-infrared photoconductivity in n-GaAs", J. Appl. Phys. 53 (6), June 1982.

IV. Selected Portions of Research Proposal Submitted to National Science Foundation.

Research Proposal Submitted to National Science Foundation

by

Williams College, Williamstown, Massachusetts

FAR INFRARED EMISSION FROM SHALLOW DONORS
IN OPTICALLY PUMPED n-Ge

Principal Investigator:

Fielding Brown
Professor of Physics
Williams College, Department of Physics

Abstract

We propose to study the far infrared (FIR) emission spectrum of shallow donors in n-type germanium under conditions of intense far infrared optical pumping and to explore the possibility of FIR laser action in the n-Ge system. We show that substantial population inversion can be produced on a number of transitions between excited states of donors and that corresponding gain cross sections are large enough to provide laser action. Powers of the order of watts are predicted at wavelengths in the range 100 μ to 3mm, and continuous (magnetic or stress) tuning is possible over large fractional band widths. We show that laser action is also possible in n-Si and in n-GaAs. If successful, this work will provide a fully tuneable, moderately intense, solid state laser source for application in spectroscopy, and communications.

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I. Introduction

The spectroscopy of hydrogen-like donors in n-type germanium and silicon stands now as one of the most thoroughly studied and best understood branches of solid state physics.¹ The bound states of electrons in these donors have been examined in detail by many workers largely through studies of excitation (absorption) spectra and through spectral measurements of induced photoconductivity. Yet few attempts have been made^{2,3} to observe these same spectra in emission, i.e. to study the radiation emitted by excited electrons on their return to lower bound levels and to the donor ground state. The reason for this oversight appears to be that the method used for excitation, impact ionization, necessarily results in considerable heating of the conduction band (CB) electrons. For instance the spectra of Thomas and Fan² clearly show that electrons exist plentifully at energies as high as 6 meV above the bottom of CB during impact ionization corresponding to an electron temperature $T_e \sim 70K$. A pseudo-thermal equilibrium then prevails in which most electrons are to be found in CB and few in bound states of donors. Complete recombination of ionized donors and electrons is then infrequent, the kinetic energy of CB electrons being delivered to the lattice through acoustical phonon emission. Under such conditions it is not surprising that Thomas and Fan² observed only about 10^{-6} watts emitted over the entire spectrum from $25cm^{-1}$ to $140cm^{-1}$.

The purpose of what follows is to show that, through optical pumping using an intense far infrared (FIR) laser, it is possible to excite electrons from the ground state of shallow donors to the conduction band

without appreciable heating of the resulting conduction electrons. With this method of excitation it is then possible to study the emission spectra of recombining electrons under more favorable conditions, i.e. with higher emission intensities.

An important object of the work we propose is therefore to make such a study. Of particular interest in this connection will be an examination of lines associated with even parity levels (e.g. 2s, 3s etc.) since such lines have been difficult or impossible to observe in earlier absorption or photo-conductivity studies but will be accessible here in emission.

We also show that an inversion of the population between certain excited donor levels is possible under FIR optical pumping. The strength of these transitions is enough to result in laser action at several FIR wavelengths.

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